Chapter 18
Soil Management Practices to Reduce Hardpans and Compaction in Sandy Soils of North Carolina, USA

Alam Ramirez Reyes, Josh Heitman, Michael Vepraskas, and Ekrem Ozlu

Abstract Soil compaction is a common issue in cultivated sandy soils of North Carolina (NC). The use of heavy equipment, field traffic, and frequent tillage at the same depth causes compaction and the formation of hardpans. Compaction is undesirable because it reduces pore space, nutrient uptake efficiency, and soil water storage, all of which contribute to lower crop yields. Tillage, cover crops, and soil amendments have been shown to alleviate compaction in NC. This chapter focuses on the sandy soils of NC which are predominantly located on the coastal plain. We highlight the variation in soil types across the state and some prior work on soil compaction. We also discuss some opportunities for future work.

Keywords Soil compaction · Tillage · Cover crop · Soil carbon · Soil health · Smart depth tillage · Subsoiling · Ripping

18.1 Compaction and Issues Associated with Compaction

Soil compaction is defined as the simultaneous increase in mass of physical particles in a certain volume and reduction of porosity in soil. A soil is said to be compacted if it has high bulk density, high penetration resistance, and low permeability (DeJong-Hughes 2018). Soil compaction is a common issue in modern agriculture and a major contributor to soil degradation in many parts of the world.

A. R. Reyes · E. Ozlu (✉)
Vernon G. James Research and Extension Center, Tidewater Research Station, North Carolina State University, Plymouth, NC, USA

Department of Crops and Soil Sciences, North Carolina State University, Raleigh, NC, USA
e-mail: eozlu@ncsu.edu

J. Heitman · M. Vepraskas
Department of Crops and Soil Sciences, North Carolina State University, Raleigh, NC, USA

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In the southeastern USA, compaction from agricultural operations is most prevalent in soils with sand and loamy sand textures in their Ap and E horizons. Sandy soils generally have a single-grain soil structure. When trafficked, the sand grains are readily compressed, and bulk densities can reach over 1.80 g cm^{-3} which can stop the elongation of most crop roots. Because sands do not shrink on drying to any appreciable extent, compact soil layers will develop a massive structure, with no structural cracks. On drying, the massive layers with high bulk density develop a high mechanical impedance that stops root elongation.

Wheel traffic-induced compaction occurs anytime that agricultural equipment passes over a field because plastic deformation of soil pores, particularly the macropores, is caused by the pressure exerted by tires of the equipment being used (Keller et al. 2019). This type of compaction is found near the soil surface and will be referred to as *topsoil compaction* as it is found primarily in the Ap horizon. *Subsoil compaction* of E and B horizons also occurs to form laterally continuous dense layers known as hardpans or tillage pans that can restrict root growth to the topsoil layers. Topsoil compaction can normally be disrupted with spring tillage using most plows and disks to depths of approximately 10 in. Hardpans are formed below the Ap horizon when tractor tires roll in a furrow and compress the exposed E or B horizons. These compressed zones are buried as the furrow is filled, and over time they extend laterally below the portion of the field that has been trafficked (Vepraskas 1984). At any depth, compaction is undesired in agriculture because it reduces crop yields by limiting root growth, reducing nutrient uptake efficiency, and reducing the amount of water plants can access during the growing season (Obour and Ugarte 2021). However, subsoil compaction is a particularly difficult challenge because its correction requires tillage to depths of 16 inches in some cases.

Tillage is usually the first option farmers select when trying to reverse the effects of compaction because tillage decreases bulk density and increases porosity; however, the benefits tillage provides are short lived and must be performed annually (Strudley et al. 2008). Additionally, most tillage operations with disks or moldboard plows are not performed deep enough to break apart hardpans below the Ap horizons. In these cases, special plows called "subsoilers" are used to pull a steel shank through the hardpan to leave a slit approximately 2 inches wide for roots to grow through.

Another option for farmers to mitigate compaction is the use of cover crops. In the short term (< 2 years), effects of cover crops on soil properties have been variable based on soil type, cover crop species, and climate (Blanco-Canqui et al. 2011). The effects of cover crops of soil properties tend to become more consistent when observed in long-term trials (> 10 years). Long-term cover crop adoption causes bulk density decreases, infiltration rate increases, water content increases, and aggregate stability increases (Blanco-Canqui et al. 2011) suggesting that cover crops may be an effective strategy to manage compaction.

In the remainder of this chapter, we highlight the soils of NC, prior work on compaction and productivity in NC, and new opportunities to address challenges with compaction in sandy soils. Sandy soils in NC are predominantly found in the eastern part of the state in the coastal plain. The largest compaction concern in these

sandy soils is the formation of hardpans. NC soils are susceptible to hardpan formation because of continuous intensive tillage and sandy subsoil horizon such as an E (Vepraskas et al. 1986). As a result, effective compaction mitigation strategies must be implemented to ensure lasting crop productivity in NC.

18.2 Soils of North Carolina

Ultisols are the dominant soil order of NC, accounting for approximately 90% of the state. These are older mineral soils that have been weathering for hundreds of thousands to millions of years (Daniels et al. 1999) under a warm, humid climate that receives approximately 50 in. of rain per year. These Ultisols have multiple horizons consisting of A, E, and Bt horizons. The sandy Ultisols have coarse-textured A and E horizons that can be 12 to more than 20 in. thick that are overly more clayey Bt horizons. Alfisols, Entisols, Histosols, Inceptisols, and Spodosols can also be found in small portions of the state (NRCS 2023). Common Ultisol soil series that have compaction problems include Norfolk (Typic Kandiudults), Wagram (Arenic Kandiudults), and Goldsboro (Aquic Paleudults) among others (NRCS 2023).

The largest soil region is the coastal plain that comprises 45% of the state (Fig. 18.1). The coastal plain is an area of river- and ocean-deposited sediments. Topography is flat with elevations varying from sea level to 650 feet above sea level (Daniels et al. 1999). The coastal plain can be further divided into the upper and lower coastal plain regions. The upper coastal plain is above 275 ft. This area has Piedmont igneous and slate belt rocks underneath marine sediments with some areas being eroded enough that the rock formations are exposed. Farms in the lower coastal plain are sometimes converted wetlands that had artificial drainage installed.

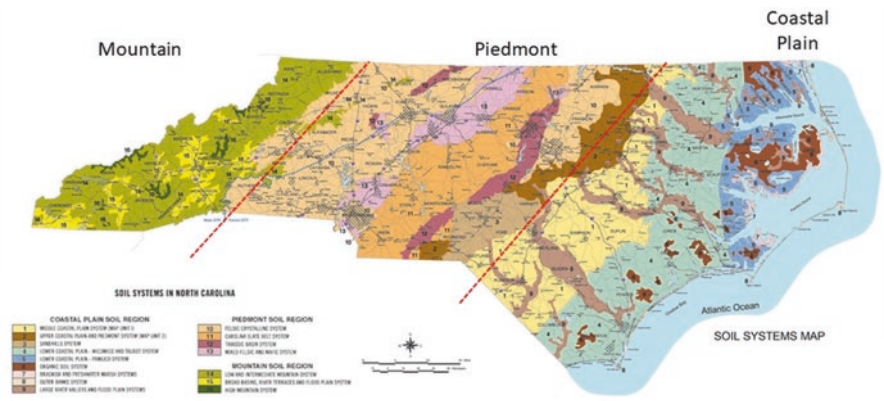

Fig. 18.1 Soil systems map of North Carolina grouped by color. (Daniels et al. 1999. North Carolina State University, Department of Soil Science)

An example of sandy soils found in the lower coastal plain is presented below, in Fig. 18.2. This is a typical soil with sandy A horizon and clayey subsurface horizons. The Tidewater region within the lower coastal plain is dominated by marine sediments and areas of poorly drained soil (Daniels et al. 1999). It includes the Blackland farms' soils that are very high in organic matter. The sandy Ultisols are most common in the coastal plain land region with clayey Ultisols found in the Piedmont land region (Fig. 18.2).

Approximately 39% of the state is in the Piedmont, which is a complex of weathered metamorphic and igneous rocks with saprolite being the dominant parent material (Daniels et al. 1999). These soils are moderately deep, well drained, and slowly permeable in a rolling to hilly area between the mountains and the coastal plain (Daniels et al. 1999). The elevation varies from 295 to 1495 feet. Oak and pine forest dominate this area. Farms typically require forest clearing, but do not require artificial drainage. The rolling topography allows for water erosion which has removed the original sandy surface layers. These soils tend to be clayey and have better structure than their coastal plain counterparts and are less prone to compaction problems (Fig. 18.2).

The mountain region covers 16% of the state. Topography in this region is variable with mountain ridges, steep valleys, broad basins, river plains and floodplains (Daniels et al. 1999). Agriculture in these areas is restricted to basins, floodplains and river plains. Spruce and fir are the most common vegetation with some areas in the high mountains restricting plant growth because of winter wind sweep and ice.

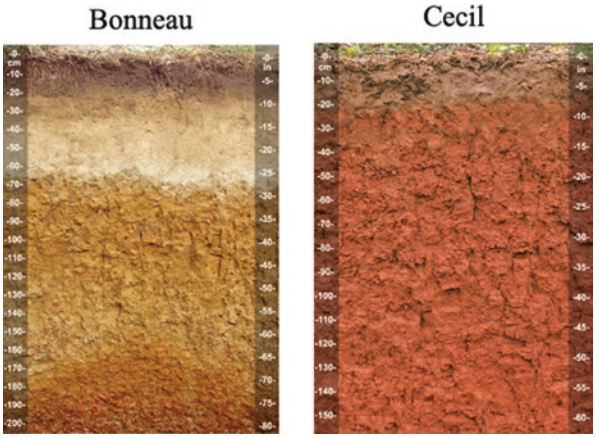

Fig. 18.2 Two Ultisols found in NC (photo courtesy of John Kelley). The Bonneau soil (Arenic Paleudult) is found in the coastal plain and has sand or loamy sand textures from 0 to approximately 30 in. This soil is susceptible to subsoil compaction with hardpans forming in the E horizon between 10 and 15 in. The high bulk density and massive structure of the hardpan prevent roots from growing through. The Cecil soil (Typic Kanhapludults) is found in the Piedmont and has a sandy loam A horizon and clay loam Bt horizon beginning at 8 inches. The Bt does not form root-restricting layers because its aggregated structure provides cracks for roots to follow into the deeper soil layers

The dominant parent materials are felsic rocks and metasedimentary formations. Elevations in this region vary from 1495 to 6680 feet. Between the three major soil regions, there are transition zones with mixed soil types (Fig. 18.1). The soils in the mountain land regions form on steep slopes and tend to be fine textured as well with fewer compaction problems as found in the coastal plain.

Soils of NC not only vary at the state scale but also at the field level. In a single field, there may be multiple soil types that require different management strategies to be as productive as possible (Duffera et al. 2007). Although there are many different soil types in general, the soils of North Carolina are leached, intensely weathered, have high clay contents in the subsurface horizons, and require fertilizer and lime to maintain crop productivity.

18.3 Management Strategies to Alleviate Compaction in North Carolina

Soil compaction is common on agricultural land in North Carolina because of heavy traffic from agricultural machinery and continuous tillage at the same depth. Consequences of compaction are at risk of becoming worse as agriculture machinery continues to get larger and heavier (Keller et al. 2019). An example of both topsoil compaction and hardpans occurring because of machinery being operated while too wet and with improper tire selection and continuous tillage is pictured below in Fig. 18.3.

Although tillage has historically been the main management strategy to mitigate compaction, intensive tillage such as moldboard plow, chisel plow, and disking are not recommended strategies to mitigate compaction in NC. While these kinds of tillage do provide some benefits in the short term, in the long term, they decrease organic matter and have higher evaporation, runoff, and erosion (Woodley et al. 2019), thus decreasing soil quality. Additionally, hardpans can form with continuous tillage. The results of intensive tillage for 50 years in the coastal plain of NC are

Fig. 18.3 Machinery causing compaction through wheel traffic and hardpans by continuous tillage

Fig. 18.4 An example of weak soil structure, low organic matter, and water stress due to long-term conventional tillage practices in the coastal plain of North Carolina

shown in Fig. 18.4. Long-term disking resulted in a soil that has low water-holding capacity, low organic matter, no structure, and a hard pan. The crops in this soil are exhibiting restricted root growth and water stress.

To avoid the negative consequences of intense tillage, no till is recommended in NC. No till increases residue cover on soil, increases infiltration, reduces runoff, and increases soil water content (Wagger and Denton 1992). Water infiltration into soil and soil water storage are correlated with bulk density and soil porosity. As bulk density decreases, and thus porosity increases, water infiltration should increase. This suggests that compaction is being alleviated by no till. Additionally, in a Casville sandy loam (fine, mixed, mesic, Typic Kanhapludult), no till increased carbon content and reduced erosion. As carbon content decreases, the more intense tillage became. No till had the highest carbon content at 2%, disking had a 1.26% carbon content, and moldboard plow + disking tillage had the lowest carbon content at 0.36% (Meijer et al. 2013). This is due to an increase in carbon oxidation because tillage has loosened the soil and porosity increased allowing for more oxygen to oxidize carbon than in a no till soil. In the same Casville soil, no till also reduced soil erosion predicted by LIDAR. Soil erosion increased to −1, −192, and −1897 Mg/ha, respectively, in a no till, disking, and moldboard plow + disking tillage management (Meijer et al. 2013).

No till may provide these benefits without decreasing crop yields on the coastal plain. Wagger and Denton (1992) demonstrated that corn yields were higher in no till compared to chisel tillage on an Eunola sandy loam (Aquic Hapludult). Five-year crop yield averages were 7.72 Mg/ha in chisel till, compared to 8.04 Mg/ha in no till for corn. Soybean yields were not affected by tillage treatment in this case. On an Aycock fine sandy loam (Typic Paleudult), both corn and soybean yields were slightly higher under no till than yields under chisel plow tillage. Corn yields averaged over 3 years were 5.14 Mg/ha (no till) compared to 4.73 Mg/ha (chisel) (Denton and Wagger 1992). Soybean yields averaged over 3 years were 1.64 Mg/ha (no till) and 1.43 (chisel) (Denton and Wagger 1992).

Fig. 18.5 A hardpan in a field management under no till for a long term. Field is located on a coastal plain in Beaufort County, NC

While no till has been shown to provide many benefits in the coastal plain, no till cannot break apart a hardpan. An example of this is shown in Fig. 18.5. Although this field has been under no till management for over 20 years, there is still a hardpan. Note how root growth stops abruptly at the hardpan and no roots are present below the hardpan. In cases like these, deep ripping is recommended to break a hardpan; however, ripping does not always have a positive effect on crop yields. While deep ripping or subsoiling will break a hardpan and increase rooting depth, it does not always increase crop yields (Vepraskas et al. 1987). The most important factor that will determine if deep ripping will be beneficial to crop yield is precipitation (Vepraskas et al. 1987). Years with adequate precipitation and precipitation distribution result in crops being able to get their moisture and fertility needs from the soil above the hardpan. As a result, deep ripping will be most likely to increase yield on dry years. Since we cannot predict future precipitation, the soil property that best predicts if ripping will result in yield increases is aggregate size in the hardpan (Vepraskas and Wagger 1990). Dense layers in an aggregate soil have planes of weakness or cracks for roots to grow through the pan and reach subsoil horizons (Vepraskas and Guthrie 1992).

Another management strategy recommended in NC is the use of cover crops. Cover crops help improve soil health by fostering increased soil biological activity, especially when multispecies cover crop systems are used (Franzluebbers et al. 2021). Other observed benefits were increases in cumulative C mineralization and increased total soil nitrogen (Franzluebbers et al. 2021). Cover crops are not without their challenges. In dry years, water depletion caused by cover crops is significant (Ewing et al. 1991), but it can be alleviated with subsoiling. When cover crops are used and ripping is performed, the influence of cover crops dominates during early crop growth, and influence of ripping dominates in the later growing season (Ewing et al. 1991). This suggests the worst combinations of factors during dry years that growers should take care to avoid are a hard pan that is not ripped and where cover crops are grown.

Some work has explored the use of amendments such as biochar to improve soil physical conditions. Biochar is a charcoal-like soil amendment that is made from organic materials burned at high temperatures in the absence of oxygen. In the NC coastal plain, biochar has been shown to decrease bulk density and improve soil-water characteristics (Walters and White 2018). Bulk density decreased with biochar application, decreasing more as the biochar application rate grew (Walters and White 2018). Total porosity of soil also increased, but the permanent wilting point increased, too. This suggests that plant available water may also decrease; however, this was not detected in the study (Walters and White 2018). Despite some potential benefits of biochar, the application rates required to achieve these benefits were cost prohibitive for growers.

18.4 Future Research Opportunities

It is unlikely that a single management practice will be enough to alleviate soil compaction, and instead multiple strategies should be employed to eliminate compaction. For example, conservation management practices will help reduce bulk density, increase organic matter in the soil, and help build soil structure, but conservation tillage cannot break apart a hardpan. Cover crops, depending on the species, may be able to break apart a hardpan but will not provide benefits as quickly as tillage. Organic amendments, such as biochar and manure, can help alleviate compaction by increasing organic matter which reduces bulk density, increases water retention of the soil, and contributes to soil aggregation. A combination of these strategies might best be able to eliminate compaction, but little work has been done on the interactions on some of these compaction alleviation strategies.

Deep ripping will break apart a hardpan, but ripping at a deep depth will result in large amounts of unnecessary fuel consumption, especially where clayey horizons are encountered. Ripping at the depth of the hardpan may not destroy the hardpan because the depth of the hardpan is not consistent. Thus, the normal lifting and dropping of the tillage implement are not enough. Smart depth tillage, a tillage depth monitoring system that automatically adjusts depth based on bulk density or prior mapping of bulk density, is an area of interest.

Certain cover crops with deep tap roots may be particularly effective at increasing organic matter and porosity at depths deeper than tillage is performed. However, it is unlikely that even cover crops with strong tap roots be able to penetrate subhorizon hardpans. In these cases, cover cropping after ripping may allow roots to penetrate deep into the soil profile, providing the benefits of cover crops at much deeper depths than previous studies have observed. The openings made by ripping may not last long enough for cover crops to establish deep roots.

The interactions between cover crops, ripping, and biochar should be investigated. We hypothesize that inserting biochar at the depth that ripping is performed will create openings in hardpans that last much longer than opening created by ripping alone. These openings would last long enough that cover crop roots may grow

deep into the soil profile; however, for biochar to be economically feasible, the biochar applications should be restricted to soils that are sandy and poorly structured where biochar applications rates will have positive impacts. This could potentially allow soil to form aggregates below the A horizon and restore soil structure or offer a means to "prop" the subsoiling slit open longer.

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